



WHO/EOS/94.10
Distribution: Limited
Original: Russian

WORLD HEALTH ORGANIZATION

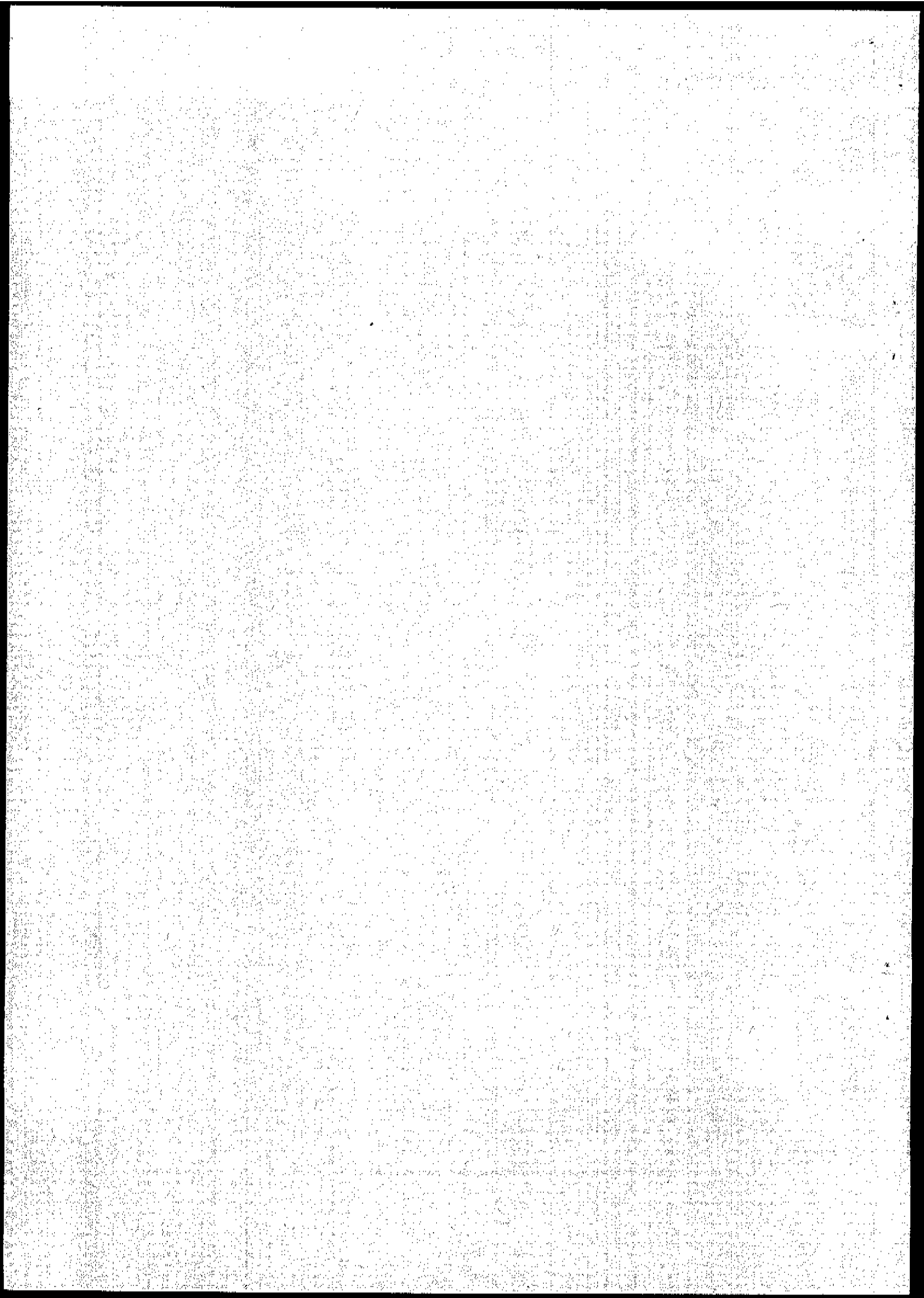
**International Programme on the Health
Effects of the Chernobyl Accident**

(IPHECA)

'Epidemiological Registry' Pilot project

**RECONSTRUCTION OF ABSORBED DOSES FROM EXTERNAL
EXPOSURE OF THE POPULATION LIVING IN
AREAS OF RUSSIA CONTAMINATED AS A RESULT OF
THE ACCIDENT AT THE CHERNOBYL NUCLEAR POWER PLANT**

**GENEVA
1994**





**RECONSTRUCTION OF ABSORBED DOSES FROM EXTERNAL
EXPOSURE OF POPULATION, LIVING IN AREAS OF RUSSIA
CONTAMINATED AS A RESULT OF THE ACCIDENT AT THE
CHERNOBYL NUCLEAR POWER PLANT**

**V.A. Pitkevic, V.V. Duba, V.K. Ivanov, A.F. Tsyb,*
V.M. Sersakov, A.V. Golubenkov, R.V. Borodin, V.S. Kosyh♥**

***Medical Radiological Research Centre of the Russian
Academy of Medical Sciences, Obninsk**

**♥Typhoon Scientific Production Company
Rosgidrometa, Obninsk**

CONTENTS

	Page
1. Introduction	2
2. Constructing a model of the dispersal of radionuclides in the atmosphere	2
3. Reconstruction of radionuclide fall-out density	10
4. Reconstruction of the spatio-temporal characteristics of radionuclides dispersal on the basis of a 'local fall-out' model	13
5. Reconstruction of absorbed doses from external exposure to passing radioactive clouds and fall-out	24
6. Conclusion	35
7. References	36

This document is not issued to the general public, and all rights are reserved by the World Health Organization (WHO). The document may not be reviewed, abstracted, quoted, reproduced or translated, in part or in whole, without the prior written permission of WHO. No part of this document may be stored in a retrieval system or transmitted in any form or by any means - electronic, mechanical or other without the prior written permission of WHO.

Ce document n'est pas destiné à être distribué au grand public et tous les droits y afférents sont réservés par l'Organisation mondiale de la Santé (OMS). Il ne peut être commenté, résumé, cité, reproduit ou traduit, partiellement ou en totalité, sans une autorisation préalable écrite de l'OMS. Aucune partie ne doit être chargée dans un système de recherche documentaire ou diffusée sous quelque forme ou par quelque moyen que ce soit - électronique, mécanique, ou autre - sans une autorisation préalable écrite de l'OMS.

1. INTRODUCTION

In order to carry out epidemiological research for the IPHECA project on the influence of radiation factors on the health of people, living in centres of population areas contaminated as a result of the accident at the Chernobyl Nuclear Power Plant, a knowledge of the amount of external and internal exposure to the thyroid gland and the whole body is crucial. Above all it is important to know the absorbed doses received by the population during the first year after the accident, since this was the most significant time as far as possible health effects are concerned. Methods and evaluations documented in the literature, in [1] and [2] for example, use data on the fall-out of various radionuclides on the basis of a single approximation of instantaneous radionuclide intake into the environment [2]. With varying degrees of accuracy, spatio-temporal fall-out characteristics have basically been established for caesium-137, and, to a lesser extent for iodine-131. Therefore, seven years after the accident at the Chernobyl Nuclear Power Plant, it is crucial that an attempt is made to reconstruct the complete dynamic picture of radioactive contamination of Russian territory, taking into consideration current data on the temporal 'behaviour' of the source of accidental radionuclide emission into the atmosphere. When assessing the amounts of radiation, a comprehensive approach can be taken, covering the physical processes of radionuclide emission from the reactor where the accident occurred, meteorological conditions at the time, detailed measurements of caesium-137 fall-out density on CIS territory, a large number of measurements of fall-out density of 'short-lived' radionuclides, air exposure dose rate measurements in centres of population and various other factors. Such an approach will enable us to determine absorbed doses in centres of population, where radiation parameters were not measured at all.

2. CONSTRUCTING A DISPERSAL MODEL OF RADIONUCLIDES IN THE ATMOSPHERE

For a detailed reconstruction of temporal dependence of exposure dose rate in a centre of population where the systemic hourly measurements of the rate were made from the moment when radioactive contamination occurred, the most reliable method is to use the results of dispersal modelling of radionuclides in the atmosphere (DMRA). Existing exposure dose rate measurements can be used to make any necessary adjustments to the modelling results. Note also that only the use of DMRA allows a complete physical picture of radioactive contamination to be formed, which corresponds to the meteorological situation at the time of radionuclide emission from the stricken reactor of Chernobyl and to the physical emission parameters, and also to establish the level of 'short-lived' radionuclide contamination in the atmosphere and the surface soil. The use of DMRA also allows contamination parameters of sections of land surface to be measured, for which exposure dose rate and radionuclide content in the environment were not recorded at the appropriate time.

A number of studies have been published, some of the results of which have been expounded in [1] for example, using DMRA to describe the radioactive contamination of various sections of land surface. These data basically contain maps showing cumulative fall-out densities of caesium-137 and, much less often, iodine-131. The accuracy of measurement of the density field of caesium-137 fall-out, especially on Russian territory, is extremely low. In order to obtain the necessary spatio-temporal picture of radioactive contamination ($q(t;x,y)$ - the density of surface soil contamination with any radionuclide and its concentration by volume in the atmosphere near ground level $p(t;x,y)$ at the point with geographic coordinates (x,y)) we used a regional dispersal model, taking account of three-dimensional turbulent diffusion of radioactive aerosol and gaseous materials in the atmosphere, which is described in detail in [3]. For the purposes of constructing the model, a three-dimensional wind field was designed, to also take account of the principle of mass balance and the relief of the earth's surface. The principles for constructing a balanced wind field based on meteorological measurements are also explained in detail in [3]. The height of the boundary layer of the atmosphere was taken to be 2 km. The period between 6 April and 21 May 1986 were modelled and results were calculated for six hour intervals.

For the purposes of modelling using the Monte Carlo method on a regular network of geographical coordinates (x_i,y_j) , the functions $q(t_k;x_i,y_j,s,a)$ were calculated and $p(t_k;x_i,y_j,s,a)$, where t_k represents time intervals from the moment radioactive material began to be emitted; s is the type of radionuclide emitted; a is the physical state of the emitted substance (aerosol particles or gaseous phase).

The linear superposition of products, which is regionally averaged according to radionuclide fall-out density $\langle q(t;x,y,s) \rangle$, onto ionising gamma-constants for the basic radionuclides, is obviously proportional to the function $P\gamma(t;x,y)$, describing temporal dependence of exposure dose rate on fall-out in settlements with the coordinates (x,y) . However, it is extremely difficult to achieve an acceptable level of accuracy in a dispersal model of all basic dose-forming radionuclides for each settlement, because of a lack of many necessary data on the power of the source of radionuclide emissions and in sufficient measurements in the area. Therefore it is impossible to use the model functions $q(t_k;x_i,y_j,s,a)$ to reconstruct the exposure dose rate directly. A description of one approach for solving this problem follows.

Function $\langle p(t;x,y,s,a) \rangle$ allows us to evaluate the dose of external exposure absorbed by the population from passing radioactive clouds and the internal dose from exposure due to inhalation intake of radionuclides.

The DMRA result essentially depends on the power of the radionuclide emission source $Q(t,h,d,s,a)$, where h is the height of the emission, d is the characteristic size of aerosol particles, in which the radionuclides are dispersed (for aerosol particle emission). By definition, $Q(t,h,d,s,a) \times dt \times dh \times dd$ is the activity emitted in intervals of time (t,dt) ; of heights (h,dh) and of linear dimensions of aerosol particles (d,dd) .

Since the physical characteristics of the emission source are usually unknown, DMRA studies seek to solve the inverse problem first (see [1], [4] for example) - working out the parameters of an "effective" source that would best account for the contamination of a given area of land by a radionuclide whose levels in the surrounding area had been measured in considerable detail after the emission. This kind of calculation has been done (see [1], [4] for example) in the zone 'near' Chernobyl for the dispersion of ^{137}Cs , Sr^{90} , $\text{Pu}^{239} + \text{Pu}^{240}$ and for ^{137}Cs and ^{131}I in areas further away from the plant. In the present study we make no attempt to deduce the characteristics of an "effective" source that would account for the radioactive contamination of Russia, since our task is to determine the functions $p(t;x,y,s,a)$ and $q(t;x,y,s,a)$ for the main dose-forming radionuclides ^{137}Cs , ^{134}Cs , ^{136}Cs , ^{131}I , ^{132}Te , ^{133}I , $^{140}\text{Ba} + ^{140}\text{La}$, $^{95}\text{Zr} + ^{95}\text{Nb}$, ^{103}Ru , ^{106}Ru , ^{141}Ce , ^{143}Ce , ^{144}Ce , ^{125}Sb , ^{99}Mo . However we do not have enough measurements of the radionuclide content of the atmosphere and the soil as described above, which could be used to solve the inverse problem of atmospheric dispersion.

For the first stage in solving the problem described above, data from [1] and [5] were used to obtain the temporal dependence of the power of the emission source $Q(t,h,d,s,a)$ for ^{137}Cs , ^{131}I and ^{144}Ce . Here, we also used the results obtained from the migration model of "elementary" emissions of unit activity with time increments of three and six hours from the moment of the accident at Chernobyl until 20 May 1986. The DMRA for 'elementary' sources (the distribution $Q(t,h,d,s,a)$) according to the height of emission h was taken to be even: 500-2000 m over the first three days and 100-500 m over the later period; the capture coefficient of the radioactive material by the subjacent surface was assumed to be 10%) allowed us to establish three time intervals of emission, the meteorological conditions for which were the most favourable for carrying radioactive material over Russian territory. The dispersion picture in the time intervals determined above can be described qualitatively as follows:

1. 27-29 April 1986 - initial dispersion of radioactive material towards the north-east from Chernobyl, shifting eastwards and then, after passing over the western part of Brjansk oblast in Russia, dispersion north-eastwards in the direction of Tula oblast. This migration has been well documented, especially in [1] and [4] as mentioned above.
2. 7-10 May 1986 - dispersion in a south-westerly direction, with a subsequent shift towards the north (over the territory of Belarus) and then having passed over the whole of Belarus from midday, 11 May 1986 to 20 May (approximately), it passed over a considerable part of the western and southern territories of Russia and Ukraine.
3. 15-19 May 1986 - dispersion northwards from Chernobyl, over the eastern half of Belarus and part of Russia, subsequently shifting towards the east and finally the south. Here, the emission of radioactive material in the period described became mixed with that emitted during the second interval determined. The two emissions merged over Russian territory during the period 16-20 May.

Here, it is appropriate to note that the second and third intervals of possible emission of radioactive material described above, practically coincides with the intervals of a sharp increase in the radionuclide concentration by volume in the air above the stricken reactor at Chernobyl [5]. The dispersion trajectories outlined above, for the second and third intervals of emission, have not been considered in the literature we have been able to consult. Therefore, the results should be regarded as preliminary and require further verification and reproduction by other authors.

Taking the above explanations as a first approximation to a solution of the given task, without solving the inverse problem of dispersion, temporal dependences of the emission output of ^{137}Cs , ^{131}I , ^{144}Ce were selected according to data in [1] and [5]. The resultant model for ^{137}Cs dispersion was then also used to reconstruct the functions $q(t;x,y,s,a)$ and $p(t;x,y,s,a)$ of the 'volatile' products of the accident; ^{131}I - ^{132}Te , ^{133}I ; ^{144}Ce - ^{141}Ce , ^{143}Ce . Here, the function $Q(t,h,d,s,a)$ was regulated for generalized data from various authors on the general activity emitted by various radionuclides [5], [6], [7], [8], [9]. In Figure 1, the dark stripes indicate the time dependences of the emission output of the 'basic' radionuclides indicated above. The aerosol fraction was taken to be 0.3 of the general emitted activity throughout the emission period. The light stripes indicate analogous dependences for radionuclides, on the assumption that they were transported in the atmosphere via the same aerosol particles as the corresponding 'basic' radionuclides. Here, we used the proportions of activities in the fuel of reactor No. 4 prior to the accident and the decomposition of 'short-lived' radionuclides from the moment the Chernobyl accident occurred, and also the assumption that ^{132}Te was emitted in aerosol form only.

By way of example, Figure 2 shows a dynamic picture of the dispersion of ^{137}Cs in the atmosphere - the concentration by volume of radionuclides in the troposphere (at a height of 1 m). Results were obtained using the methodology described in detail in [3]. In the top right-hand corner of each slide, the date is given for which the concentration by volume (in relative units) has been estimated. The slides in Figure 2, produced using the RECASS geographic formation computer system [3], provide a more complete picture of the dispersion.

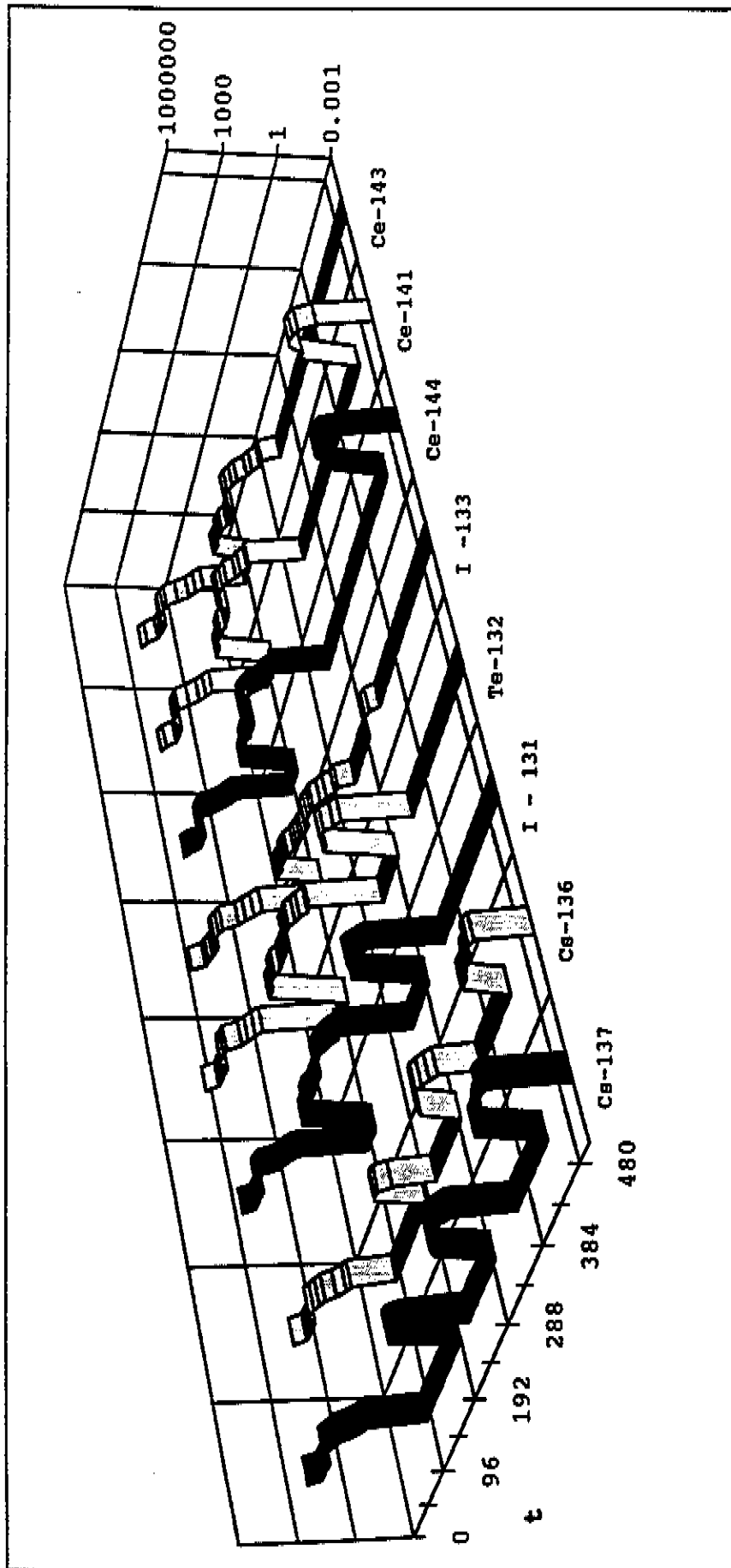


Figure 1. Dependences of emission output of radionuclides (K Curies/hours) on time(hours) from the moment the Chernobyl accident occurred. The light stripes are the result of reconstruction; the dark stripes were used to create the atmospheric dispersal model.

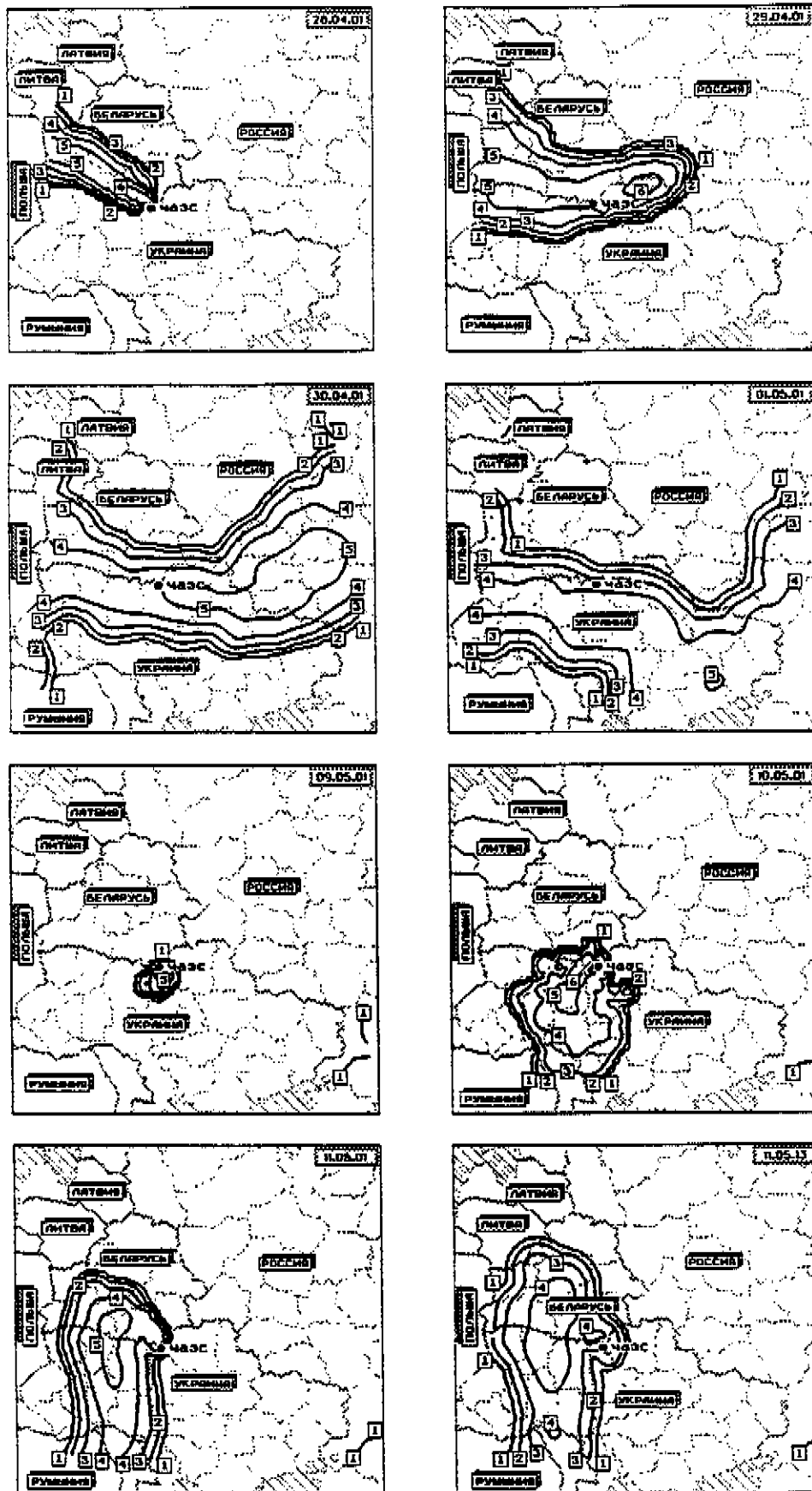


Figure 2. Concentrations by volume, estimation according to the atmospheric dispersal model, of ^{137}Cs (relative units) in the air at various points in time after the accident at Chernobyl (calendar month and date, Moscow time). A higher number on the isopleths signifies a tenfold increase in concentration by volume.

The words on each of the 8 maps read from left to right, top to bottom are as follows: Latvia, Lithuania, Belarus, Russia, Poland, Chernobyl, Ukraine, Romania.

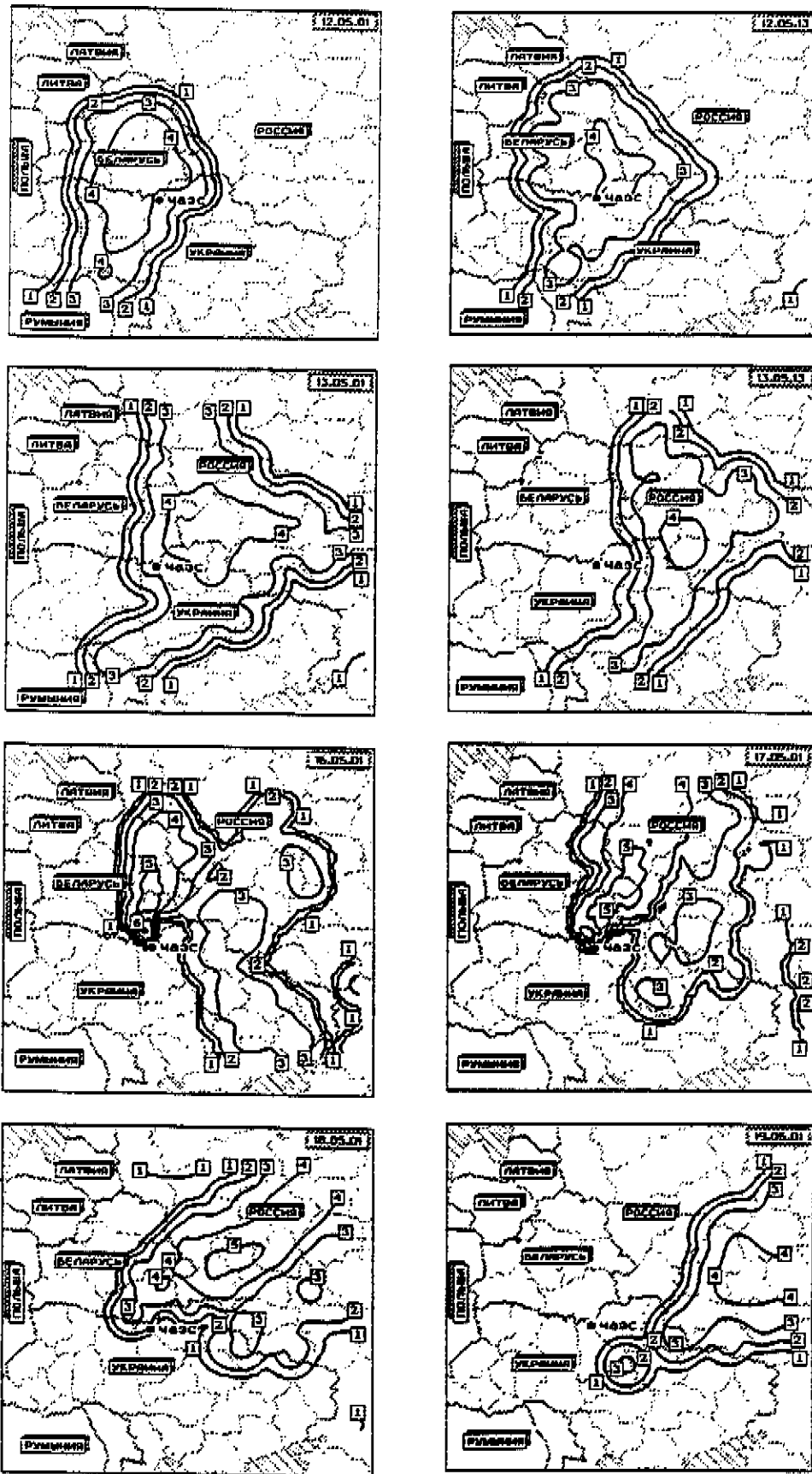


Figure 2 (continued). Concentrations by volume, according to the atmospheric dispersal model, of ^{137}Cs (relative units) in the air at various points in time after the accident at the Chernobyl (calendar month and date, Moscow time). A higher number on the isopleths signifies a tenfold increase in concentration by volume

The words on each of the 8 maps read from left to right, top to bottom as follows: Latvia, Lithuania, Belarus, Russia, Poland, Chernobyl, Ukraine, Romania.

3. RECONSTRUCTION OF RADIONUCLIDE FALL-OUT DENSITY

Further evaluations of the functions $\langle q(t;x,y,s,a) \rangle$ and $\langle p(t;x,y,s,a) \rangle$ (as before the signs $\langle \rangle$ signify averaging according to the vicinity of the settlement being examined, the size of which depends on its type) are based on fall-out densities measured in the vicinity of the settlement or reconstructed values of fall-out density of various radionuclides on to the subjacent surface, which are hereafter designated $q_r(t;x,y,s)$.

The fall-out density of the basic dose-forming radionuclides in settlements was reconstructed on the basis of a detailed statistical analysis of the gamma-spectrometry of 2867 soil samples, collected by various organizations and establishments throughout the CIS between 1986 and 1988. The results of this analysis are expounded in [9]. In the present study, it seems appropriate to give a brief explanation of some of the soil sampling results. Thus, in the north-east trail, as it is termed in [9] (the northern part of the 30 km zone around the Chernobyl power plant, the eastern part of Belarus (from the direction of Mozyr'-Mogilev) and the Russian oblasts of Brjansk, Kaluga, Tula, Orlov, Kursk and Rjazan), a large number of correlative and linear regressive dependences between fall-out densities of various pairs of radionuclides have been discovered in soil samples. Here, regression coefficients depend on the distance between the collection point of the sample and the Chernobyl power plant. Some of the most important dependences are given in Table 1.

The fall-out density of the radionuclides σ_2 , indicated on the left of the designated pair, can be evaluated using the relationship:

$$\sigma_2 = a + b \cdot \sigma_1,$$

where σ_1 is the measured fall-out density of the radionuclide, indicated on the right of the designated pair (Table 1); a is a coefficient equal to $-0.1b$ Curies/km² for the pair, in which the measured size is the fall-out density of ¹³⁷Cs (global fall-out level is taken to be 0.1 Curies/km²); in other cases $A = 0$.

Fall-out density relating to 'long-lived' radionuclides (¹³⁴Cs, ¹³¹I, ¹⁴⁰La, ⁹⁵Zr + ⁹⁵Nb, ¹⁰³Ru, ¹⁰⁶Ru, ¹⁴⁴Ce, ¹²⁵Sb), for which there are no given measurements in the settlements being examined, was assessed according to the correlative and regressive links established [9], taking into account the degree of 'volatility' of the chemical compounds, in which the radionuclides were dispersed in the atmosphere.

Analysis of the given gamma-spectrometries of soil samples (Table 1), collected in the 'north-east trail', established the fall-out density onto soil of ¹³¹I transported in the atmosphere in aerosol particles. The data in Table 1 show that for the 'trail' indicated, a high correlation was discovered between the fall-out density of ¹³¹I and that of ¹³⁷Cs. Thus, the correlation coefficient ranges from 0.92 to 0.73 depending on the distance from Chernobyl, which means that, for the linear regressive dependence

which has been formed between the fall-out densities of the radionuclides indicated the change in the fall-out density of ^{137}Cs (the regression equation argument) with a probability of 85-53% affects the ^{131}I fall-out density corresponding to the regression equation. Since detailed measurements of ^{131}I fall-out density were not recorded throughout the entire contaminated territory in May-June 1986, and ^{131}I fall-out data represent the most important information for assessing the possible health effects of the accident, it is necessary to accept the use of established correlative and regressive links between ^{131}I and ^{137}Cs fall-out to reconstruct ^{131}I fall-out density on the basis of detailed measurements of ^{137}Cs fall-out density. The accuracy of reconstruction of ^{131}I fall-out density on Russian territory is slightly lower than for the zones 'close' to the Chernobyl plant and for Belarussian territory, where the correlation between ^{131}I and ^{137}Cs fall-out densities is greatest.

The coloured insert shows the reconstruction results in the form of a fall-out density map of the aerosol fraction of ^{131}I on Russian territory on 10 May 1986. The isopleths of ^{131}I fall-out density were constructed on the basis of data from our study [10], also using measurements of ^{137}Cs fall-out density [11]. The autocorrelative method [3] was used to construct the isopleths. It should be noted that when an analogous map is constructed, which takes into consideration ^{131}I fall-out in Belarus, sections of isopleths on the borders of Russia and Belarus change. Hence the need to carry out this type of study in the future in order to obtain an agreed picture of ^{131}I fall-out in the territory concerned.

TABLE 1. CORRELATIVE AND REGRESSIVE LINKS BETWEEN THE FALL-OUT DENSITIES OF VARIOUS RADIONUCLIDES, ON 10 MAY 1986

- R_1 - left boundary of distances between the sample collection point and Chernobyl, km;
 R_2 - right boundary of distances between the sample collection point and Chernobyl, km;
 r - correlation coefficient between fall-out densities measured;
 b - linear regression coefficient between densities measured;
 δ_b - relative error of the regression coefficient, %.

R_1	R_2	r	b	δ_b	R_1	R_2	r	b	δ_b
$^{134}\text{Cs} - ^{137}\text{Cs}$					$^{131}\text{I} - ^{137}\text{Cs}$				
0	30	0.981	0.540	1.6	0	30	0.879	6.125	10.7
30	60	0.987	0.530	0.9	30	60	0.874	5.216	7.1
60	140	0.979	0.565	1.8	60	150	0.919	6.766	10.9
140	220	0.985	0.534	0.6	150	230	0.795	2.925	9.0
220	310	0.997	0.589	1.2	230	400	-	-	-
310	430	0.986	0.510	0.7	400	620	0.733	3.340	10.3
430	620	0.973	0.501	0.8					
$^{140}\text{Ba} + ^{140}\text{La} - ^{137}\text{Cs}$					$^{103}\text{Ru} - ^{137}\text{Cs}$				
30	50	0.722	4.054	13.9	0	40	0.315	2.743	17.3
50	120	0.429	1.977	17.8	40	86	0.656	2.545	11.5
120	230	0.849	0.471	16.5	128	180	0.880	1.338	2.1
230	400	-	-	-	180	232	0.932	1.321	2.7
400	620	0.564	0.637	16.4	232	345	-	-	-
					345	450	0.932	1.258	2.0
					450	620	0.936	1.391	2.9
$^{106}\text{Ru} - ^{137}\text{Cs}$					$^{144}\text{Ce} - ^{137}\text{Cs}$				
0	30	0.553	1.488	11.5	0	30	0.301	6.082	12.2
30	45	0.539	1.568	6.3	30	40	0.670	4.114	8.5
45	60	0.888	0.816	6.1	40	50	0.272	2.874	9.8
60	110	0.594	0.964	11.4	50	70	0.810	1.414	6.3
110	170	0.729	0.502	4.3	70	150	0.677	0.761	15.9
170	270	0.880	0.451	3.5	150	240	0.795	0.249	11.2
390	450	0.853	0.414	3.6					
450	560	0.615	0.470	7.8					
$^{144}\text{Ce} - ^{95}\text{Zr} + ^{95}\text{Nb}$					$^{106}\text{Ru} - ^{103}\text{Ru}$				
0	30	0.947	0.327	3.5	0	30	0.910	0.584	17.4
30	40	0.928	0.350	4.2	30	40	0.423	0.399	20.1
40	50	0.955	0.342	4.3	40	50	0.658	0.270	12.6
50	60	0.970	0.299	2.9	50	86	0.858	0.258	7.1
60	90	0.838	0.306	7.3	86	125	-	-	-
90	160	0.874	0.349	6.3	125	210	0.860	0.272	4.3
160	235	0.829	0.389	9.0					
$^{144}\text{Ce} - ^{106}\text{Ru}$					$^{141}\text{Ce} - ^{144}\text{Ce}$				
0	30	0.888	2.915	5.8	0	30	0.937	0.983	6.8
30	40	0.824	2.560	4.8	30	60	0.838	1.002	5.7
40	50	0.930	2.294	6.9	60	90	0.943	1.168	6.0
50	60	0.930	1.844	5.5	90	125	-	-	-
60	70	0.753	2.137	7.2	125	210	0.883	1.056	6.4
70	160	0.745	1.301	11.7					
160	235	0.650	0.307	14.2					

4. RECONSTRUCTION OF THE SPATIAL-TEMPORAL CHARACTERISTICS OF THE DISPERSION OF RADIONUCLIDES ON THE BASIS OF A "LOCAL FALL-OUT" MODEL

The fall-out densities of 'short-lived' radionuclides (^{136}Cs , ^{132}Te , ^{133}I - aerosol fraction, ^{141}Ce , ^{143}Ce) were reconstructed on the basis of the assumption that radionuclides from a certain 'volatility' group (Group 1 - ^{137}Cs , 2 - ^{131}I , 3 - ^{144}Ce) were dispersed in the atmosphere via the same aerosol particles. The fall-out density of a 'short-lived' radionuclide pair was calculated on the basis of such an approximation, using the function $\langle q(t;x,y,s,a) \rangle$ for the 'leading' radionuclide group, which was obtained with the help of the DMRA, the relationship of the activities of the radionuclide pair being examined ('leading' and reconstructed) prior to the accident and the adjustment made for the decay of the radionuclide pair towards the end of the last fall-out interval. In order to make the results of the DMRA of 'leading' radionuclides in various 'volatility' groups correspond to data measurements (or to reconstructed data for 'long-lived' radionuclides) available for each settlement being investigated, a model of local 'effective' fall-out has been developed. This model is described below.

Let $f(t;x,y,s)$ be the fall-out rate of s type radionuclides in a unit of time at the point with the coordinates (x,y) depending on the time interval t from the moment fall-out begins in a given settlement (in order to be brief, parameters x , y and s are subsequently omitted). It is obvious that $q(t)$ for each radionuclide must equal the solution of the differential equation:

$$\frac{dq}{dt} + \lambda \cdot q = f(t), \quad (1)$$

where λ is the decay constant of the radionuclide. Since $q(t)$ is estimated in our DMRA using the Monte-Carlo method, the $f(t)$ estimate from equation (1) can result in considerable inaccuracies. Therefore, a different approach is then used to establish $f(t)$ for all radionuclides. The simplest and most reliable method is to apply a graduated approximation of fall-out rate:

$$f(t) = \sum_{i=1}^{n-1} f_i \cdot U_i(t - t_i), \quad (2)$$

where $0 = t_1 < t_2 < \dots < t_n; f_n = 0; U_i(x)$ - single graduated function.

For each elementary fall-out interval, it is easy to obtain:

$$q_i(t) = \frac{f_i}{\lambda} \cdot (1 - e^{-\lambda(t-t_i)}), t_i \leq t \leq t_{i+1}; \quad (3)$$

$$q_i(t) = q_i(t_{i+1}) \cdot e^{-\lambda(t-t_{i+1})}, t_{i+1} \leq t.$$

Finally, for each radionuclide, fall-out density can be calculated using the fall-out function $f(t)$ in accordance with (2), adding up (3) for all fall-out intervals.

$$q(t) = \sum_{i=1}^{n-1} q_i(t) \cdot U_+(t - t_i). \quad (4)$$

For further estimates, the relationship between radionuclide concentration by volume in the air $p(t)$ and its fall-out rate $f(t)$ (vertical flow of the radioactive material) is important. A general expression for $f(t)$ can be derived from [1], for example:

$$f(t) = \int_{d_1}^{d_2} [V_s(t, d) + \beta_0] \cdot p(t, d) \cdot g(d, t) \cdot dd, \quad (5)$$

where $V_s(t, d)$ is the gravitational fall-out rate of aerosol particles; β_0 is the parameter of adhesion of the radioactive material to the subjacent surface, depending on the area in which contamination is being investigated; $g(d, t)$ is the density of the distribution function of aerosol particles according to characteristic linear measurements. Since it was basically radionuclide dispersion over large distances which was investigated, the radionuclide was dispersed in small aerosol particles (where d is of the order of 1 micrometre). Therefore, in (5), V_s can be disregarded in comparison with β_0 , which we assume to be equal to 1 cm/s [1]. This gives the simple relation:

$$f(t) = \beta_0 \cdot \overline{p(t)}, \quad (6)$$

where $p(t)$ is the averaged radionuclide concentration by volume according to the dimensions of the particles (henceforth the averaged sign is always omitted).

In this way, relationship (6) can now be used to obtain the dependence $f(t)$ according to the results of application of the DMRA. The introduction of local 'effective' fall-out into the evaluation involves applying function $f(t)$ obtained via the DMRA, using graduated approximation (2) of the adjustment $k(x,y,s)$. The result is that the calculated function $q_r(t;x,y,s,a)$ corresponds to the measured or reconstructed radionuclide fall-out density in the settlement exactly. Since vector $\{f_i\}$ in (3) figures in the expression for fall-out density in factorial form, it follows that the adjustment $k(x,y,s)$ can be noted as follows:

$$k(x, y, s) = \frac{q_r(t_n, x, y, s)}{q(t_n, x, y, s)}, \quad (7)$$

where t_n is the time interval between the dates when the accident began and when s type radionuclide fall-out ceased in the settlement (or any later date). Then, within the framework of the "local 'effective' fall-out model" described here, the following expressions can be noted for estimating 'true' radionuclide concentration by volume in the air $p_r(t;x,y,s,a)$ and 'true' fall-out rate $f_r(t;x,y,s,a)$ taking account of (6):

$$\begin{aligned} p_r(t, s) &= k(s) \cdot p(t, s); \\ f_r(t, s) &= \beta_0(s) \cdot k(s) \cdot p(t, s). \end{aligned} \quad (8)$$

The 'true' fall-out density $q_r(t,s)$, equal to the amount measured or reconstructed in the region of the settlement at the point t_n , is then calculated according to relationships (3) and (4). Thus the approximation described provides a complete spatio-temporal picture of the radioactive contamination of any settlement using the DMRA.

As an example of how the concepts discussed here were used, Figures 3 and 4 show the reconstructed concentrations by volume of all radionuclides mentioned above in the Russian towns of Zlynka, Zlynka rayon, Brjansk oblast (a highly-contaminated zone) and Zizdra, Zizdra rayon, Kaluga oblast (boundary of the contaminated zone of Kaluga oblast). A comparison of the data in Figures 3 and 4 gives an indication of the considerable difference in terms of contamination between the settlements mentioned. Thus, we see that most of the radionuclides (except the isotopes ^{131}I and ^{132}Te) in the vicinity of Zizdra are the result of emissions which occurred on 7-17 May 1986; contamination by ^{131}I and ^{132}Te resulted from the initial emission and subsequent releases, in roughly equal amounts. On the other hand, the basic contamination of the western part of Brjansk oblast was due to the initial emissions from reactor No. 4 at Chernobyl on 27-29 April 1986. Confirmation by independent data selected by us from [5] on temporal dependences of the power of the emission source, provides firm foundations in this case, for re-evaluating available published data on absorbed doses to the thyroid gland from incorporated radionuclides of iodine.

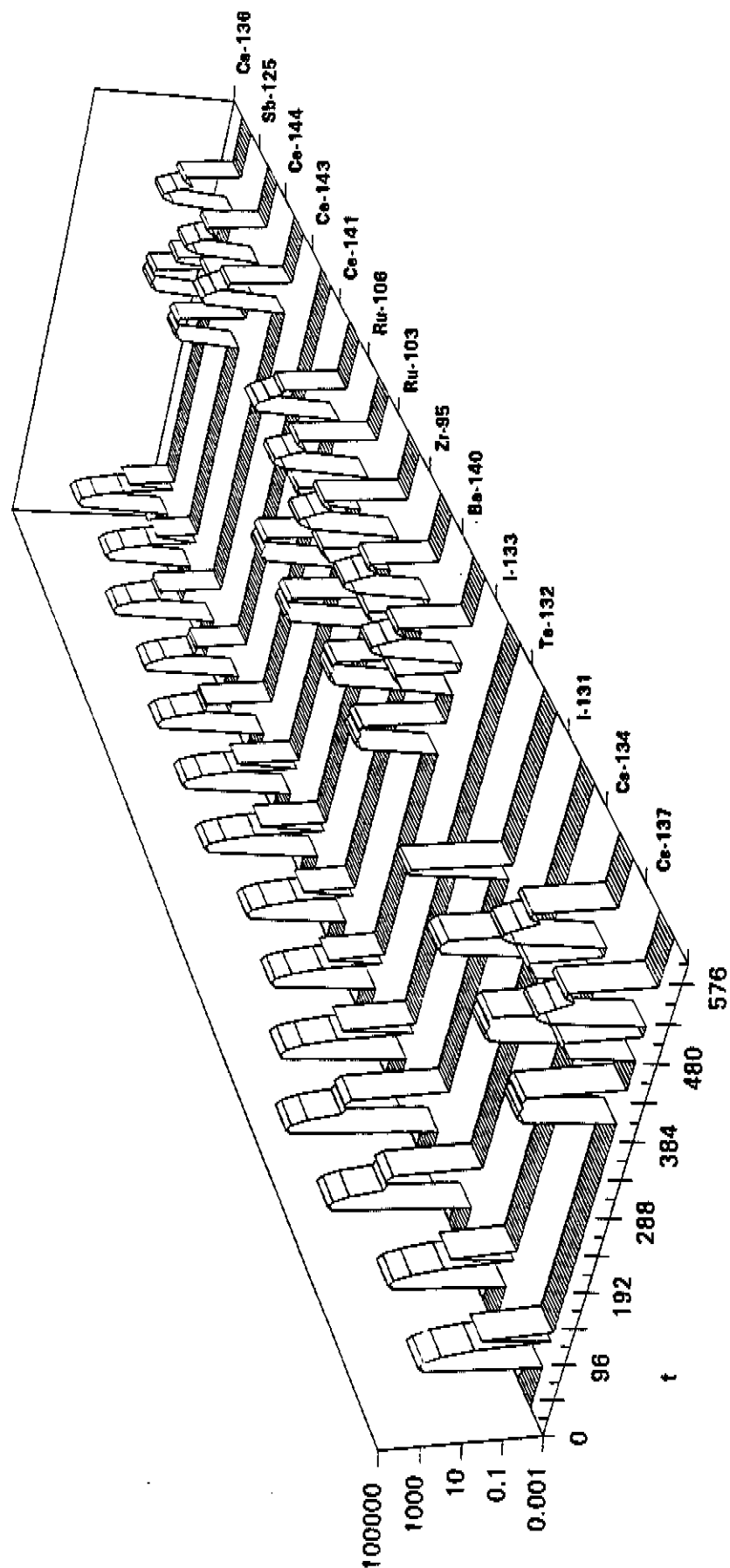


Figure 3. Town of Zlynka, Brjansk oblast
The graph shows concentration by volume (Bq/m^3) of various radionuclides in the atmosphere near ground level plotted against time, reconstructed on the basis of an atmospheric dispersal model. The time interval (hours) is calculated from the 'moment' of the Chernobyl accident

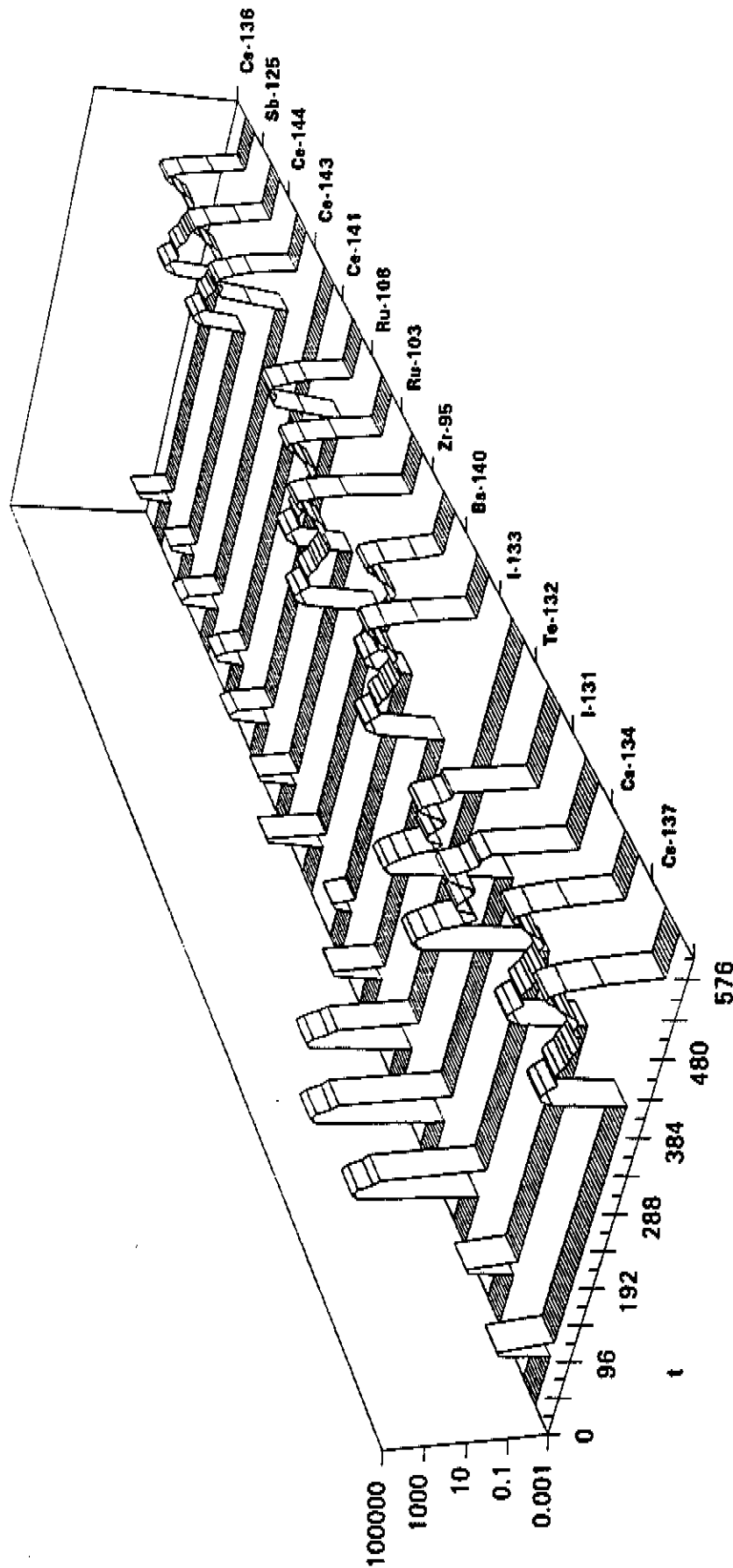


Figure 4. Town of Zizdra, Kaluzskaja oblast
The graph shows concentration by volume (Bq/m^3) of various radionuclides in the atmosphere near ground level plotted against time, reconstructed on the basis of an atmospheric dispersal model. The time interval (hours) is calculated from the 'moment' of the Chernobyl accident

5. RECONSTRUCTION OF ABSORBED DOSES FROM EXTERNAL EXPOSURE TO RADIOACTIVE CLOUDS AND FALL-OUT

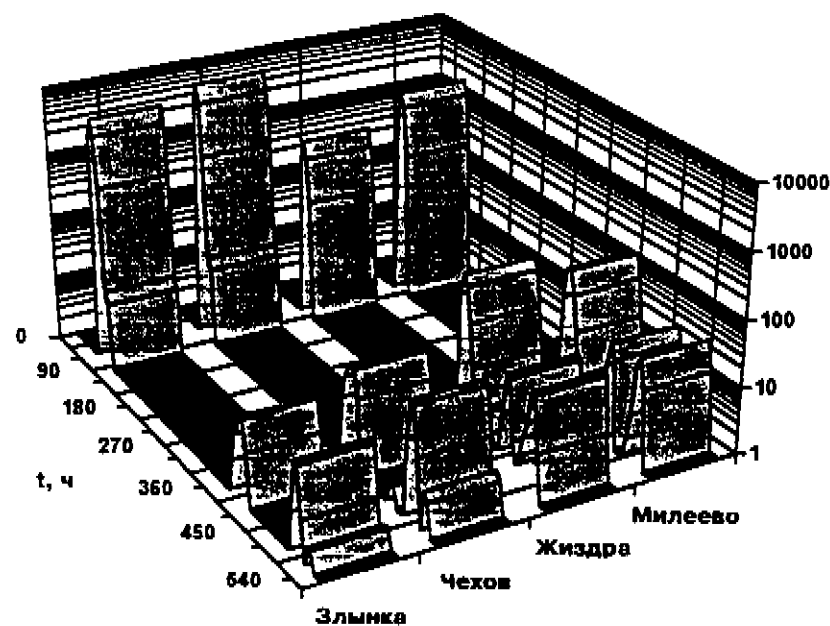
Estimated radionuclide activity by volume was used to estimate the absorbed dose rate from external exposure of inhabitants to a passing radioactive cloud. In order to obtain methodologically correct results we calculated the absorbed dose rate from monochromatic gamma-quanta, with energy between 30 kilo electron volts and 2 mega electron volts, which were evenly distributed in flat infinite strata of air 50 m thick, surrounded above and below (down to the surface of the soil) by scattering strata of air. Here, account was also taken of the scattering of gamma-radiation from a soil stratum of the required thickness. Calculations were made with the ROZ-6 computer programme [12] using a specially developed system of parameters, which describe the interaction of gamma-radiation in the range of energies indicated above with an accuracy of 10-2%. The ROZ-6 programme produces the numerical solution to the equation of radiation dispersion in one-dimensional geometry. The results of calculations for mono-energetic gamma-quanta and semi-infinite geometry which take into consideration scattering from the soil are 20% higher than results usually used for these purposes [13], for example, for energy values higher than 100 kilo electron volts. When energy decreases, the difference increases, and reaches 100% for energies of 40-50 kilo electron volts. We used the results of calculations for elementary strata, found at various heights above the surface (0-2 km), to estimate the B_s transition coefficients from activity on volume to the absorbed dose rate in 'soft' biological tissue at a height of 1 m above the soil surface, assuming that radionuclide concentration does not change in the atmospheric stratum, characterised by turbulent mixing (to the boundary stratum). In Table 2, the results of calculations of B_s are listed for a series of radionuclides. For radionuclides in the table, which have 'short-lived' secondaries, the gamma-radiation of the secondary has been taken into consideration, and the dose coefficient has been normalized to the activity of the parent radionuclide.

Figure 5 gives examples of absorbed dose rate results for a series of settlements (the towns of Zlynka and Cehov in Zlynka rayon, Brjansk oblast, and also the town of Zizdra, in Zizdra rayon and the village of Mileevo, Hvastovickij rayon, Kaluga oblast).

The absorbed doses from external exposure to passing radioactive clouds for the settlements indicated are as follows: Zlynka - 83 mrad, Cehov - 133 mrad, Zizdra - 15 mrad, Mileevo - 30 mrad. The significance of the absorbed doses discussed is that in their order of magnitude they correspond to the absorbed doses of internal whole-body exposure to ^{137}Cs and ^{134}Cs in Brjansk and Kaluga oblasts during the first year after the Chernobyl accident.

Table 2. Transition coefficients from the specific activity of a radionuclide in a volume of air (Bq/m³) to the absorbed dose rate (microrads/hour) in 'soft' biological tissue at a height of 1 m above the surface of the soil. The figures in brackets indicate the decimal order of the coefficient.

Radionuclide	B _s	Radionuclide	B _s
¹³⁷ Cs	0.1772(-1)	¹³⁴ Cs	0.4598(-1)
¹³¹ I	0.1168(-1)	¹³² Te	0.7239(-1)
¹³³ I	0.1799(-1)	¹⁴⁰ Ba	0.5607(-2)
¹⁴⁰ La	0.6695(-1)	⁹⁵ Zr	0.2171(-1)
⁹⁵ Nb	0.2248(-1)	¹⁰³ Ru	0.1467(-1)
¹⁰⁶ Ru	0.6003(-2)	¹⁴¹ Ce	0.2812(-2)
¹⁴³ Ce	0.9235(-2)	¹⁴⁴ Ce	0.1762(-2)
⁹⁹ Mo	0.8859(-2)	¹⁴⁷ Nd	0.5001(-2)
^{110m} Ag	0.8002(-1)	¹²⁵ Sb	0.1296(-1)
¹³³ Xe	0.1979(-2)	¹³⁶ Cs	0.6362(-1)
²³⁹ Np	0.5433(-2)	²⁴¹ Am	0.9591(-3)



The x-axis reads time (t) in hours.

Towns along the y-axis read from left to right as follows: Zlynka, Cehov, Zizdra, Mileevo.

Figure 5 shows the reconstructed results of the absorbed dose rate ($\mu\text{rad}/\text{hour}$) in "soft" biological tissue at a height of 1m due to radioactive clouds passing over the populated areas indicated. The x-axis shows the time interval (hours) between the current date and the date when the Chernobyl accident began.

In order to describe the exposure dose rate (EDR) due to radioactive fall-out in settlements, the reconstructed functions $q_r(t,s)$ were used, without, however using the well-known relationships between EDR and specific surface activity (which were used in [2], for example). The model EDR we obtained is "attached" to the given EDR values that were measured in each settlement between 1986 and 1987.

In order to construct a model for EDR dependence on time, the following processes were taken into account:

- Radionuclide fall-out onto surfaces unprotected by buildings, structures and turf covered landscape features - $q_r(t;x,y,s)$;
- radioactive decay of the radionuclide - λ_s ;
- shielding of gamma-radiation by a blanket of snow - $S(t)$;
- vertical migration of radionuclide in the soil - $M(t;x,y)$
- EDR data measured in the settlement during periods when there was an absence of snow cover between 1986 and 1987 - $P^{\gamma} = P^{\gamma}(t_i;x,y)$;

Taking account of these processes we can note:

$$P^{\gamma}(t) = P_0^{\gamma} + (P^* - P_0^{\gamma}) \cdot \frac{G(t) \cdot M(t) \cdot S(t)}{G(t^*) \cdot M(t^*)}, \quad (9)$$

where P^{γ} is the EDR prior to the accident, due to natural sources of gamma-radiation; (t^*, P^*) are the coordinates of a point in a plane (t, P^{γ}) , for which the condition $P^* = P^{\gamma}(t^*)$ is correct; these parameters are estimated according to EDR measurements in settlements;

$$G(t) = \sum_i K_i^{\gamma} \cdot q_i(t, s); \quad (10)$$

K_i^{γ} - ionization gamma-constant of the radionuclides.

In order to "attach" the model EDR dependence to the data measurements we will use the method of maximum probability, assuming that the measured values have a chance "background" component \mathfrak{S} with zero mathematical expectation and with dispersion which depends on the EDR. Then we can note the regression model, taking (9) into consideration:

$$P^{\Delta}(t) = P^{\Delta} \cdot F(t) + \mathfrak{S} \cdot F^{\alpha}(t), \quad (11)$$

where $P^{\Delta}(t) = P'(t) - P'_0$; $P'^{\Delta} = P' - P'_0$; $F(t)$ depends on the time factor in (9);

α is the normalized parameter in the interval [0,1]; ξ is the normally distributed chance magnitude with a zero average value and unknown dispersion s^2 (being estimated).

The parameter α should be selected so that the law of the distribution of the "background" component approaches a normal distribution. The probability function has been included for estimation of P^{Δ} and s , on the principle that the EDR measurements obtained from the data at the moment t_k of the magnitude

$$\xi_k = \frac{P_k^{\Delta} - P'^{\Delta} \cdot F(t_k)}{F^{\alpha}(t_k)}$$

are independent realizations of normally distributed chance magnitude with a zero average value and the standard deviation s . Then we can set out the estimates of the necessary parameters:

$$P'^{\Delta} = \frac{\sum_k w_k \cdot F_k \cdot P_k^{\Delta}}{\sum_k w_k \cdot F_k \cdot F_k}; \quad (12)$$

$$w_k = \frac{1}{F_k^{2\alpha}}; \quad (13)$$

$$s^2 = \frac{1}{m} \cdot \sum_{k=1}^m w_k \cdot [P_k^{\Delta} - P'^{\Delta} \cdot F_k]^2; \quad (14)$$

$$D(P'^{\Delta}) = \frac{s^2}{\sum_k w_k \cdot F_k \cdot F_k}; \quad (15)$$

$$D(s) = \frac{s^2}{2 \cdot n}. \quad (16)$$

The dispersion of EDR estimated using the model described for each moment measured is expressed as:

$$D(P_k^{\Delta}) = [D(P'^{\Delta}) + s^2 \cdot F_k^{2(\alpha-1)}] \cdot F_k^2. \quad (17)$$

The adjustment for gamma-radiation shielding $C(t)$ by snow cover in 1986 and 1987 is based on EDR data measurements recorded by the radiology laboratory of the rayon department of the State Health and Epidemiology Directorate in Ul'janovsk rayon, Kaluga oblast and the village of Ul'janovo. Processing EDR measurements recorded for the village of Ul'yanovo, taking account of the assumption that snow cover does not change EDR due to gamma-radiation from natural sources, allows us to introduce adjustment $C(t)$ for all settlements of the contaminated territory of Russia, and also to use it for subsequent time intervals. The adjustment values being used are listed in Table 3. P' is applied here with a value of $10 \mu\text{r}/\text{hour}$. In further calculations $C(t)$ is calculated by interpolating the data in Table 3 using cubic splines.

Table 3

ADJUSTMENT $C(t)$ FOR GAMMA-RADIATION SHIELDING BY SNOW COVER. THE TIME INTERVAL t , (DAYS) IS CALCULATED FROM 1 DECEMBER 1986

t, days	C (t)	t, days	C (t)
0	1.000	22	0.855
41	0.685	62	0.550
81	0.488	90	0.472
100	0.942	121	0.784
144	1.00		

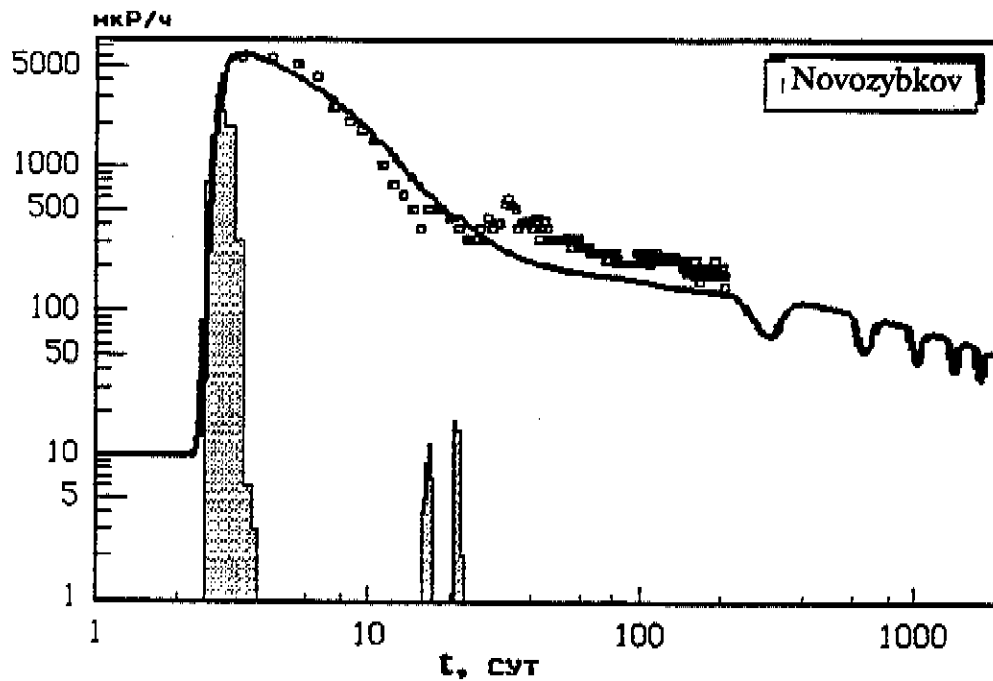
The methodology described here is intended for the reconstruction of absorbed doses from external exposure in all settlements contaminated in Russia as a result of the Chernobyl accident. These areas have many different soil types. Therefore, in order to take the vertical migration in the soil of chemical compounds containing ^{137}Cs and ^{134}Cs into consideration, we used an exponential model of radionuclide distribution [1] with the parameter L "for the extent of downward penetration in the soil" as a first approximation. Here it was also presupposed that L linearly depends on the time elapsed t between the present date and that of the accident:

$$L = a + b.t, \quad (18)$$

where parameters a and b depend on the soil type prevalent in that particular part of the settlement. Using an approximation of the accumulation dose factor (formula (49) [15]), it is easy to obtain an expression for in-air EDR from the volumetric source of gamma-quanta in the soil using the depth distribution law, and by integrating the EDR from elementary sources. A definitive expression representing this value would be too complex to be mathematically tractable. The results obtained can be presented in the form of an adjustment $M(L(t))$, taking account of the decrease in EDR due to the extent of downward penetration of radionuclides in the soil. In the 0.05-3 mev interval of energies, the adjustment described, which corresponds well to experimental data [1], depends very slightly on gamma-radiation energy and soil composition. This enables us to use "universal" dependence for $M(L(t))$, which is given in Table 4. for a height of 1 m above the "soil" surface (silicon dioxide). In the calculations, data from [16] were used according to coefficients of decreased gamma-radiation in various environments. Thus the methodology expounded means that the temporal dependence of EDR in a settlement can be completely reconstructed using the results of the model for atmospheric dispersion of radioactive material, data from measurements of radionuclide fall-out composition and EDR in the area. Figure 2 gives an example of the results of EDR reconstruction for the town of Novozybkov, Brjansk oblast (a large number of "early" EDR measurements) and the village of Mileevo, Hvastovickij rayon, Kaluga oblast (lack of "early" EDR measurements). When determining EDR from fall-out, the value of the normalizing parameter α was equal to 0, i.e. "background" parameters were not minimized. This means that all EDR values, measured up until 1 December 1987, carry the same statistical weight. As is evident from Fig. 2, the reconstruction model described provides a satisfactory picture of the data measurements available and fully determines the temporal dependence of EDR from the moment the accident occurred until the present time.

Figure 6

Graph 1. Novozybkov x - axis - time/days y - axis - μR /hour



Graph 2. Mileevo x - axis - time/days y - axis - μR /hour

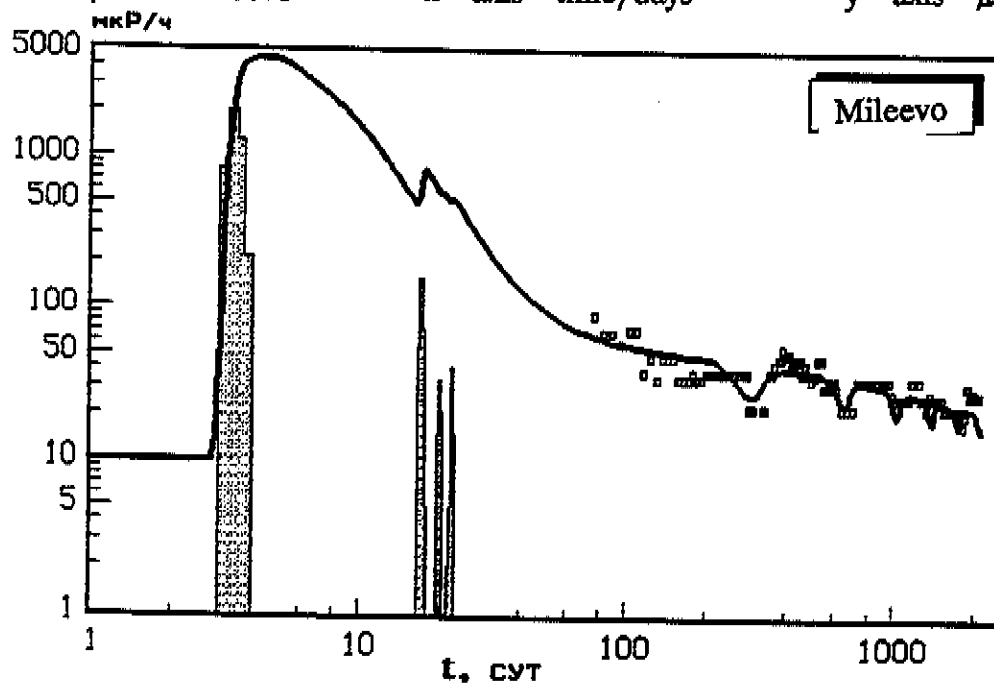


Fig. 6. Reconstructed EDR dependence on the length of interval t between the present date and the date the Chernobyl accident took place. Continuous curves - EDR model from fall-out onto the surface of the soil; Shaded rectangles - absorbed dose rate from radioactive clouds; Points - measured EDR allowing for adjustments due to the energetic dependence of the sensitivity of dosimeters used.

Table 4. Adjustment M(L) to the "degree of downward penetration" of radionuclides in the soil, taking account of the vertical migration process depending on the time interval since the accidental contamination of the locality

Parameter L - g/cm², the figures in brackets represent the decimal order of the number.

When using the table the cubic spline-interpolation should be applied as a logarithm according to L and M(L).

L	M(L)	L	M(L)
1.0(-3)	1.0000(0)	2.0(-3)	9.9701(-1)
4.0(-3)	9.9410(-1)	6.0(-3)	9.9129(-1)
8.0(-3)	9.8855(-1)	1.0(-2)	9.8588(-1)
2.0(-2)	9.7347(-1)	4.0(-2)	9.5213(-1)
6.0(-2)	9.3399(-1)	8.0(-2)	9.1810(-1)
1.0(-1)	9.0390(-1)	2.0(-1)	8.4869(-1)
4.0(-1)	7.7654(-1)	6.0(-1)	7.2704(-1)
8.0(-1)	6.8901(-1)	1.0(0)	6.5803(-1)
2.0(0)	5.5495(-1)	4.0(0)	4.4484(-1)
6.0(0)	3.7935(-1)	8.0(0)	3.3345(-1)
1.0(1)	2.9868(-1)	2.0(1)	1.9965(-1)
4.0(1)	1.2175(-1)	6.0(1)	8.7847(-2)
8.0(1)	6.8761(-2)	1.0(2)	5.6502(-2)
2.0(2)	2.9891(-2)	4.0(2)	1.5398(-2)
6.0(2)	1.0370(-2)	8.0(2)	7.8176(-3)
1.0(3)	6.2735(-3)		

The results obtained allow us to estimate absorbed doses for various population groups living in contaminated settlements. For this purpose we used coefficients of transition C_g [17] from the in-air exposure dose at a height of 1 m in the area of the settlement to absorbed doses from external whole-body exposure for various groups of inhabitants, obtained on the basis of data from individual dosimetric monitoring between 1987 and 1991. Non-linear extrapolation of the experimental data was used to obtain estimates for 1986, 1992 and 1993.

Table 5. "Exposure" coefficients C_g (sSv/R) of several groups of the population, living in settlements of various types

Group 1 - the whole population, taking account of the average relative number living in a settlement where most buildings are brick;

Group 2 - the whole population, taking account of the average relative number living in a settlement where most buildings are wooden;

Group 3 - children living in a settlement, where most buildings are brick;

Group 4 - children living in a settlement, where most buildings are wooden;

calendar group	group			
	1	2	3	4
1986	0.40	0.55	0.34	0.36
1987	0.32	0.47	0.28	0.32
1988	0.28	0.40	0.24	0.29
1989	0.24	0.33	0.20	0.26
1990	0.20	0.28	0.18	0.24
1991	0.18	0.26	0.17	0.22
1992	0.16	0.24	0.15	0.20

Some of the data obtained in this way for several groups of inhabitants and various types of PAs are given in Table 5.

Table 6 gives examples of preliminary estimates (until the parameters of the radionuclide emission source from reactor No. 4 at Chernobyl are defined more precisely) of the exposure dose due to fall-out and absorbed doses from the moment the accident occurred until the end of 1986 for some groups of inhabitants of several populated areas in Brjansk and Kaluga oblasts, in the Russian zone contaminated with radioactive material. The exposure dose due to fall-out was obtained by the numerical integration of EDR dependence on time. The following settlements have been selected to illustrate these results: the towns of Novozybkov and Klincy, several settlements in Zlynka rayon, Brjansk oblast, and also Zizdra, Uljinovo and Hvastovici rayons, Kaluga oblast, Russia.

Table 6. Estimated doses, according to the model described above, from external exposure of the inhabitants of several populated areas in Russia from the moment radioactive contamination began until the end of 1986

$\sigma_{\min} - \sigma - \sigma_{\max}$ - minimum - average - maximum ^{137}Cs fall-out density, measured around settlements, curies/ km^2 ; [11]

D_{exp} - in-air exposure dose from radioactive fall-out at a height of 1 m, P;

D_{cl} - absorbed dose from whole-body exposure to passing radioactive clouds, cSv;

H_{fall} - equivalent dose from external exposure of children to radioactive fall-out, cSv.

Populated area	$\sigma_{\min} - \sigma - \sigma_{\max}$	D_{exp}	D_{cl}	H_{fall}
Zlynka	11.5-28.6-77.9	5.000	0.083	1.749
Vyskov	9.6-29.1-47.5	6.466	0.124	2.263
Bol'sie Scerbinici	5.9-14.7-35.2	2.925	0.040	1.053
Barki	10.7-29.1-59.4	9.361	0.052	3.370
Zarec'e	27.0-39.3-57.0	11.692	0.120	4.209
Klincy	0.4-4.2-26.8	0.522	0.005	0.183
Novozybkov	1.8-16.6-38.8	1.053	0.033	0.358
Starye Bobovici	8.3-27.3-61.3	5.794	0.046	2.086
Zizdra	0.2-2.2-5.1	0.203	0.015	0.071
Korenevo	1.5-2.2--2.7	0.534	0.002	0.192
Scigri	1.3-4.8-9.1	0.756	0.003	0.272
Gorki	6.1-6.8-7.5	0.843	0.003	0.303
Ul'janovo	2.8-4.1-5.4	0.530	0.002	0.191
Dudorovskij	1.3-7.8-21.8	1.013	0.004	0.496
Afanasovo	2.3-8.4-14.3	1.213	0.006	0.437
Krapivna	2.3-6.1-9.1	1.274	0.006	0.459
Melihovo	1.3-7.2-18.3	1.345	0.004	0.484
Hvastovici	0.2-1.8-5.6	0.701	0.003	0.380
Mileevo	2.7-7.9-16.2	1.411	0.026	0.508
Mileevo	0.1-3.2-9.5	1.022	0.030	0.368
Lovatjanka	7.1-11.7-20.3	1.455	0.009	0.524
Resseta	3.2-8.5-21.4	1.427	0.010	0.514

The data in Table 6 represent absorbed doses from external exposure to radioactive clouds and fall-out in comparison with the measured density of ^{137}Cs contamination around settlements. In particular there is a correlation dependence between D_{exp} and the average contamination density of the locality with ^{137}Cs , although the spread of values from the linear regressive dependence is sufficiently great. It must also be emphasized that D_{exp} , estimated according to the methodology described, depends considerably on both the results of EDR measurements around the settlements in question, and on a knowledge of the exact points in the settlements where measurements were taken between 1986 and 1987. For the purposes of epidemiological research into the influence of radiation on the health of the population, the methodology expounded here is sufficiently precise.

6. CONCLUSION

Thus the methodology outlined in this report provides for reconstructing the basic parameters of radiation levels in populated areas, situated on territory contaminated as a result of the accident at the Chernobyl nuclear power station. Those parameters are:

- fall-out density of the basic dose-forming radionuclides on the surface of the soil in and around each populated area for any time interval after radioactive contamination of the locality began;
- radionuclide concentration by volume in the atmosphere near ground level for any time interval after the radioactive contamination of the locality began;
- dependence of absorbed dose rate on time and absorbed doses from external exposure of various population groups to passing radioactive clouds;
- dependence of absorbed dose rate on time and absorbed doses from external exposure of various population groups to radioactive fall-out;

Thus the results obtained allow us to supplement existing estimates, and in some cases to reconstruct the extent of exposure of the population living in areas contaminated as a result of the Chernobyl accident with greater precision. A comprehensive approach is used which takes account of all basic processes, including meteorological conditions determining the behaviour of radionuclides emitted from reactor No. 4 into the environment. This approach enables estimation of the extent of external and internal exposure, which is crucial to the completion of the "Epidemiological Registry" project for those cases where more precise estimates of individual absorbed doses are not available. Note also that the data obtained allow verification of the absorbed doses measured with "biological dosimetry" methods which are currently being developed.

7. REFERENCES

1. Chernobyl: radioactive contamination of natural environments. [in Russian] Ed. Ju. A. Izraelja, Leningrad: State Scientific-Technical Hydro-meteorological Publishing House, 1990.
2. Golikov, V.Yu., Balonov, M.I. & Ponomarev, A.V. Estimation of external gamma radiation doses to the population after the Chernobyl accident. - The Chernobyl papers, Vol. 1 - Doses to the Soviet population and early health effects studies Ed. Steven E. Merwin and Michail Balonov. Washington, REPS, 1993, pp. 247-288.
3. Vakulovskij, S.M., Sersakov, V.M., Golubenkov, A.V. et al. Computer technology to analyse radiation levels of territories contaminated as a result of the Chernobyl accident. [in Russian]. Radiaciya i risk, 1993, issue 3, pp. 36-61.
4. Borzilov, V.A., Klepkova, N.V. Effect of meteorological conditions and release composition on radionuclide deposition after Chernobyl accident. The Chernobyl papers, Vol. 1 - Doses to the Soviet population and early health effects studies. Ed. Steven E. Merwin and Michail Balonov. Washington, REPS, 1993, pp. 47-70.
5. Buzulukov, Yu.P. & Dobrynin, Yu.L. Release of radionuclides during the Chernobyl accident. The Chernobyl papers, Vol. 1 - Doses to the Soviet population and early health effects studies. Ed. Steven E. Merwin and Michail Balonov. Washington, REPS, 1993, p. 3-22.
6. Khan, S.A. The Chernobyl source term: A Critical Review. Nucl. Safety, 1990, vol. 31, No.3, pp. 353-374.
7. Gudiksen, P.H. et al. Chernobyl source term, Atmospheric dispersion, and dose estimation. Health Physics, 1989, vol. 57, No. 5.
8. Begicev, S.N., Borovoj, A.A., Burlakov, E.V. et al. The fuel of reactor No. 4, at Chernobyl. [in Russian]. Preprint, Institute of Atomic Energy - 5268/3. Moscow 1990.
9. Pitkevic, V.A., Sersakov, V.M., Duba, V.V. et al. Reconstruction of radionuclide fall-out composition in areas of Russia due to the accident at the Chernobyl nuclear power station. [in Russian]. Radiaciya i risk, 1993, issue 3, pp. 62-95.
10. Reconstructed ^{131}I fall-out density in parts of Russia after the accident at the Chernobyl nuclear power station. [in Russian]. Radiaciya i risk, 1993, issue 3, Appendix 1, Part 2.

11. Specific surface contamination of areas of Russia by the ^{137}Cs isotope as a result of the accident at the Chernobyl nuclear power station. [in Russian]. Radiaciya i risk, 1993, issue 3, Appendix 1, Part 1.
12. Averin, A.V., Voloschenko, A.M., Kondratenko, T.A. et al. The ROZ-6.4 one-dimensional ordinates neutrons, gamma-rays and charged particles transport codes. Int. Topical Meeting, Advances in Mathematics, Computations and Reactor Physics, April 28 - May 2, 1991, Pittsburgh, USA, vol. 4, p. 30.
13. Gusev, N.G. & Beljaev, V.A. Radioactive emissions in the biosphere. Reference book, [in Russian] Moscow: Energoatomizdat, 1991.
14. Shutov, V.N., Bruk, G.Y., Balonov, M.I. et al. Cesium and strontium radionuclide migration in the agricultural ecosystem and estimation of the internal doses to the population. Ed. Steven E. Merwin and Michail Balonov, Washington, REPS, 1993, pp. 167-220.
15. Izrael' Ju.A. & Stukin, E.D. Gamma-radiation from radioactive fall-out. [in Russian]. Moscow, Atomizdat, 1967, p. 84.
16. Hubbel, J.H. Photon cross sections, Attenuation coefficients, and Energy absorption. Coefficients from 10 keV to 100 GeV. Washington, USA Dep. Comm., NBS. 1969.
17. Savkin, M.N. Late effects of the Chernobyl accident on the environment and health within the 30 km zone. [in Russian]. Radiaciya i risk, 1993, issue 3, pp. 96-121.

RECONSTRUCTION DENSITY OF ¹³¹I FALL-OUT (Ci/km²) DUE TO THE CHERNOBYL ACCIDENT (ON 10 MAY 1986)

